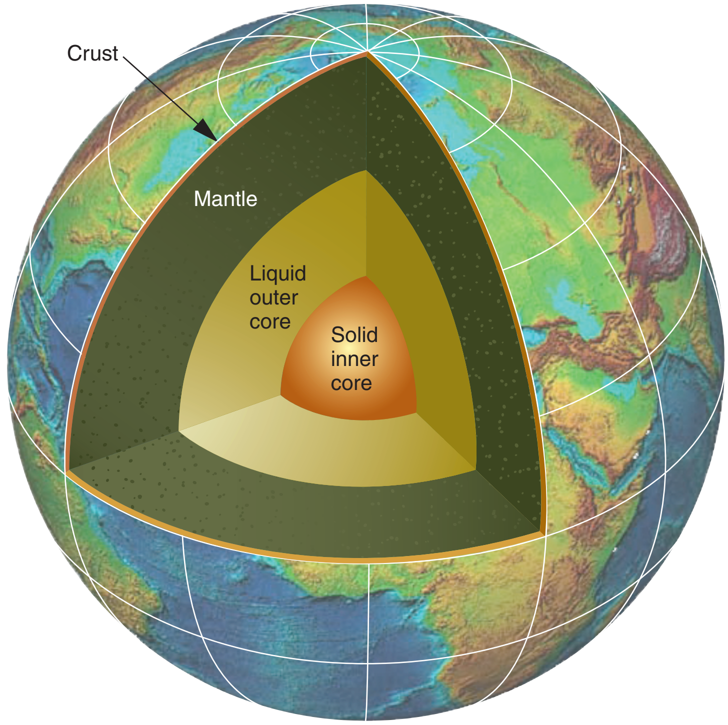
A Calculated Journey to the Center of the Earth



A cutaway view of Earth shows the planet's solid inner core composed mostly of iron, surrounded by a molten outer core, followed by a mantle and a thin crust of rocky, silicate material.

PLANET Earth still holds many scientific mysteries. One that particularly intrigues scientists is how and when the planet's core formed. In Jules Verne's 1864 novel *Journey to the Center of the Earth*, an inquisitive scientist hikes down the inside of an Icelandic volcano to examine the inner Earth. Uncovering the truth of what lies beneath Earth's crust is even more difficult in life than it was in Verne's fiction. Scientists have yet to travel through the planet. Instead, they use indirect methods such as examining meteorites and conducting seismic studies to deduce how and when Earth's core formed.

However, a technique developed by a team of Livermore scientists has, for the first time, allowed researchers to measure the permeability of molten iron compounds in olivine, a mineral in the upper mantle, under conditions that mimic those at the center of planetesimals—the precursor bodies to new planets. Because this physical parameter is experimentally constrained, geophysicists have a key measurement to help them evaluate models of core formation and examine other geologic processes, such as heat flow, tectonics, volcanism, and magnetism. Understanding these mechanisms will help unlock the secrets of Earth and other terrestrial-like planets, meteorites, and planetesimals.

The Core Issue

Using meteorites and seismic records as clues, scientists have determined that all terrestrial planets have cores. Earth has a solid inner core composed mostly of iron, surrounded by a molten outer core, followed by a mantle and a thin (5- to 50-kilometer-deep) crust of rocky, silicate material. Most scientists agree that density is the driving force behind this layered formation, resulting in chemical fractionation—a process in which substances in a mixture separate or segregate depending on their physical and chemical properties. In this critical process, denser materials such as iron migrate toward the center, while lighter materials such as silicates are forced toward the surface. However, scientists have yet to determine how this segregation occurs.

"Several models have been proposed," says experimental geophysicist Jeff Roberts, who leads the Livermore research. For example, the "magma ocean" model starts with a planet that has a large molten region—the magma ocean layer in which molten metals and minerals commingle. In this model, gravity draws the molten metal through the lighter liquids in a lava-lamp-like process until the metals and silicates separate into layers. The percolation model, on the other hand, proposes a slower mechanism in which the denser molten metal trickles down between solid silicate mineral grains, akin to water percolating through sand.

Squeeze, Heat, and Image

To evaluate the percolation model, researchers must determine the percolation threshold—the point at which the molten metal begins to migrate through, or permeate, the matrix of minerals rather than form isolated pockets. The percolation threshold varies a few percent based on the wetting or nonwetting behavior of the materials involved. For example, the estimated threshold for nonwetting metal mixtures ranges from 3 to 7 percent by volume. Estimates for permeability, a parameter that measures a material's ability to transmit fluid, vary even more, by many orders of magnitude.

Directly measuring the percolation threshold under temperatures and pressures relevant to core formation has been impossible up to now. Roberts and his team, which included geochemists Rick Ryerson and Julien Siebert and physicist John Kinney, changed all this. With funding from Livermore's Laboratory Directed Research and Development Program, they combined experiments and simulations to determine the percolation threshold and permeability of molten iron sulfide migrating through a crystalline olivine matrix at temperatures and pressures representative of Earth's interior.

To create realistic samples of what would have existed early in Earth's geologic history when the core was forming, the team examined the composition of meteorites. Ryerson and Siebert prepared the samples by mixing finely ground olivine crystals, one of the most common minerals in Earth, with iron sulfide or an iron–nickel sulfide powder. The proportion of molten metal to crystal olivine in the mix varied from 2 to 13 percent. "This proportion spans the estimates established for the percolation threshold—the amount of molten metal needed to form a continuously connected melt," says Siebert. The concentration of nickel varied from 0 to 10 percent, a range that researchers believe matches the proportion of nickel in Earth's core.

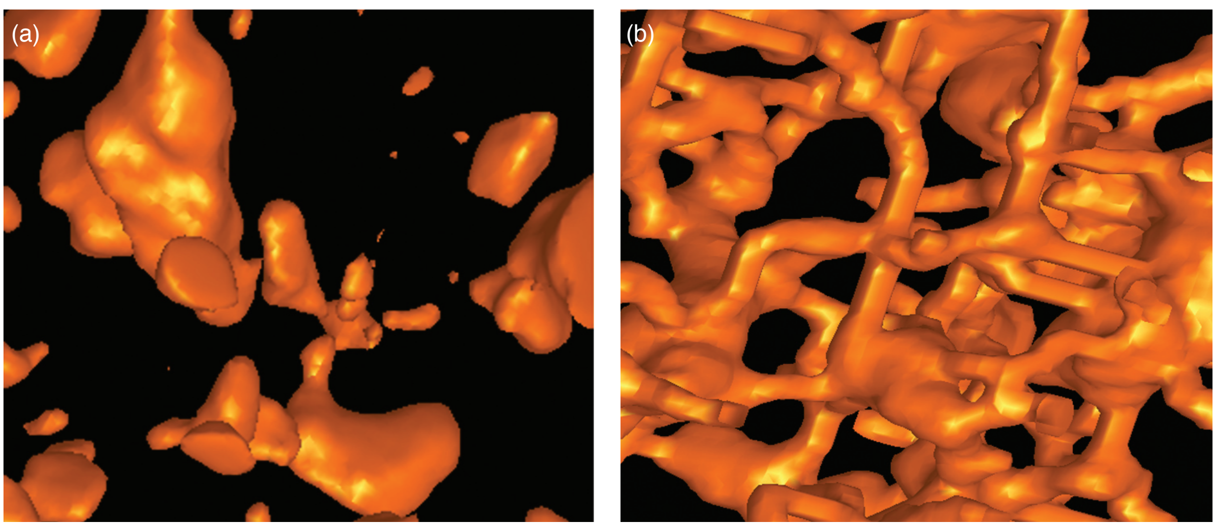
Samples, each about the size of a pencil eraser, were created with a piston cylinder press, using techniques originally developed by Livermore's William Minarik to study Earth's formation. (See *S&TR*, December 1996, pp. 21–23.) For 24 hours, the samples were subjected to temperatures of 1,350°C and pressures of 1 gigapascal, conditions believed to be characteristic of Earth's interior early in the planet's formation. The samples were then quenched, freezing the molten metal within the olivine matrix.

To examine the structure of this metal, Roberts imaged the samples at Lawrence Berkeley National Laboratory's Advanced Light Source using an x-ray tomography beamline and software Kinney developed while researching bone structure. (See *S&TR*, September 2006, pp. 20–22.) Their efforts yielded striking three-dimensional images showing the structure of the metal–olivine samples with a spatial resolution of 1.6 micrometers.

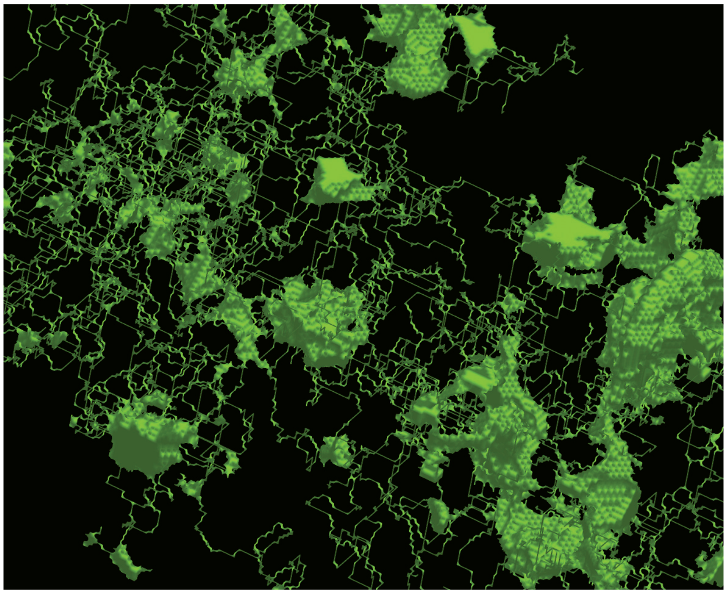
"The metal is more opaque to x rays than the olivine matrix, making it easy to distinguish the structure of the melts," says Kinney. In the images, percolating and nonpercolating melt fractions clearly differed. The distribution of the metal melts, their degree of interconnectivity throughout the matrix, and the pockets of melted metal were also apparent.

Going with the Flow

Next, the team used the x-ray computed tomography data in computer simulations to determine a sample structure's permeability. For these calculations, each image was divided into discrete computational (mathematical) spaces, called lattices. The team then used a lattice Boltzmann solver, an algorithm that speeds the calculation, to solve the Stokes flow equation for the defined lattices. In this type of flow, the inertial forces are smaller than the viscous forces, and flow is laminar.



X-ray computed tomography images distinguish the structure of molten metal within an olivine matrix. (a) In a sample with a 4-percent melt of iron sulfide, the molten metal exists primarily in pockets. (b) With a 6-percent melt of iron–nickel sulfide, these pockets are connected by tiny channels of metal.



Computer calculations indicate that permeability depends on small tubules of molten metal connecting melt pockets.

With the resulting images and calculations, the scientists calculated permeabilities for different melt fractions and put limits on previous estimates. They also established the percolation threshold for various percentages of melt to olivine and determined that percolation may have contributed to planetary core formation. For example, the team calculated that a 100-kilometer-diameter meteorite with a melt fraction of 10 percent has a permeability of approximately 2×10^{-15} square meters. This measurement indicates that the molten metal would migrate about 1.5 centimeters per year.

"Iron-rich cores apparently formed in these types of objects within about 3 million years," says Roberts, "which corresponds to a melt velocity of about 3.3 centimeters per year. Thus, the calculated migration rates are consistent with percolation being the formation mechanism." He added that the team's calculated permeabilities probably form a lower boundary. "We used an average grain size of 45 micrometers for the olivine," he says. "The larger grain sizes observed in meteorites would support an even higher permeability."

A Closer Look at Other Processes

Research using the team's techniques is examining core formation and other processes. Livermore researchers are collaborating with colleagues at the University of Minnesota and the University of California at Davis to explore deformation in more detail. For example, in some samples, the molten metal formed stand-alone "melt pockets." The research team wants to determine whether deforming and twisting the sample—a shearing-type action that often occurs during earthquakes and other geologic events—might cause the pockets to connect and allow the metal to flow.

In a project funded by the Department of Energy's Office of Basic Energy Sciences, the researchers are attempting to estimate permeability using the measured electrical conductivity for a sample of interconnected melt. "An interconnected melt is a continuous web of essentially very tiny wire," says Roberts. "In theory, we could run a current through it to learn more about the melt's structure."

Researchers are adapting the team's measurement technique to examine other geologic materials. For instance, a collaboration involving the U.S. Geological Survey and the University of Oregon is using the Livermore approach to study the explosive nature of volcanic materials. "Basically, they are imaging different volcanic glasses such as tuff and pumice and calculating the permeability of gases in the materials," says Roberts. "With those results, they can determine which conditions will allow gas to flow through and escape and which will trap it in pockets and possibly cause an explosion."

The Livermore technique, which measures a previously unobtainable physical parameter, also has applications beyond the team's initial focus. "Now that this method exists," says Roberts, "we'll be interested to see where the research goes from here."

—Ann Parker

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For further information contact Jeff Roberts (925) 422-7108 (roberts17@llnl.gov).